

Thermal expansion of liquid Ti-6Al-4V measured by electrostatic levitation

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The liquid density of Ti-6Al-4V was measured over a temperature range from 1661 to 1997 K that included undercooling by as much as 280 K. The sample was levitated in an electrostatic levitator and video imaging technique was used to capture the volume changes as a function of temperature. Over the temperature range the liquid density can be expressed by $\rho_{\text{liq}}(T) = 4123 - 0.254 (T - T_m)$ kg/m³, where the melting temperature T_m is 1943 K. The corresponding volume expansion coefficient is $\alpha_{\text{liq}} = 6.05 \times 10^{-5} \text{ K}^{-1}$ near T_m . © 2006 American Institute of Physics.
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Ti-6Al-4V (or Ti64) alloy was introduced in 1954 by adding to titanium 4% vanadium to stabilize the β phase and 6% aluminum to stabilize the α phase. While the thermal properties of solid Ti64 have been studied comprehensively in the past years, data for molten Ti64 are relatively rare at best and their accuracy is uncertain even if they exist. This is primarily due to contamination caused by chemical reaction with container walls in its molten phase. The thermophysical property data of molten Ti64, especially the density, are needed for an accurate casting simulation and phase transformation modeling. Lack of such data often prompted to adopt molten titanium data in simulating Ti64 processes. In this letter we are reporting the thermal expansion data of molten Ti64 and they will be compared with those of molten titanium.¹

For other properties of molten Ti64, Cezairliyan *et al.* measured the melting temperature of Ti64 using the pulse heating method,² and using the same method Kaschnitz *et al.* measured C_p of liquid Ti64 above the melting temperature.³ The enthalpy of Ti64 was measured by Brooks *et al.* using the drop calorimetry technique.⁴ The surface tension and viscosity have been measured by Fecht *et al.* using the electromagnetic levitation technique in the reduced gravity environment provided by the parabolic flights.⁵

To avoid contamination and chemical reaction with the container wall, we have adopted containerless electrostatic levitation (ESL) technique to isolate the sample from the container as well as gases surrounding the sample. For thermophysical property measurements we have used various noncontact diagnostic techniques associated with the ESL.^{6,7} Ti64 becomes volatile at high temperature and can cause position instability if a single laser beam is used for heating. It can also change its original composition if the sample is allowed to evaporate too long. The newly improved tetrahedral laser heating arrangement⁸ circumvents this difficulty. During the heating period, four equal powered laser beams keep the sample at a predetermined position instead of being pushed away from it by imbalanced force field. Such arrangement allowed very fast measurements of thermophysical properties of Ti64 with increasing accuracy.

The Ti64 samples provided by the United Technology Corporation were ground to roughly spherical shape having

approximately 2.5 mm diameter. They were housed in a stainless-steel vacuum chamber which was typically evacuated to 10^{-8} Torr. A 200 W neodymium doped yttrium aluminum garnet laser is used for the sample heating.

Levitated Ti64 sample was first melted to 2028 K for 7 s before we turned off the heating power and allowed the sample to cool radiatively. The molten sample undercooled by as much as 282 K. The sample temperature was measured using a single color pyrometer operating at 700 nm and it was calibrated with respect to the melting temperature, $T_m = 1943$ K, assuming a constant emissivity for the molten sample in the temperature range of the measurement. During the free cooling process, both the sample temperature and the video images of the sample were simultaneously recorded. Since the shape of the molten sample levitated by ESL is axisymmetric around the vertical axis, taking a single side image of the sample was sufficient to extract full volume information. The recorded video images are digitized and the sample volume is extracted from each video frame by fitting the image with Legendre polynomial.⁷

Both the temperature profile and the specific volume so obtained are shown in Fig. 1. The liquid Ti64 cooled from 1977 to 1661 K with 282 K undercooling before it recalesced to T_m and became a β phase solid. The β phase solid cooled until β to α transition took place. The β phase solid seemed to have undercooled to about 170 K, which

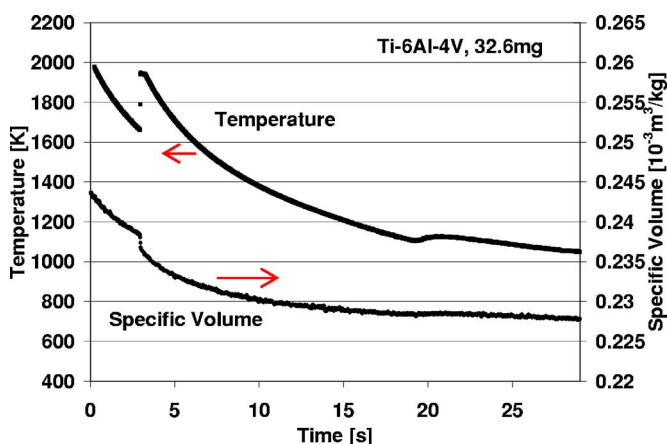


FIG. 1. (Color online) Radiative cooling curve and the specific volume of Ti64 that were measured simultaneously.

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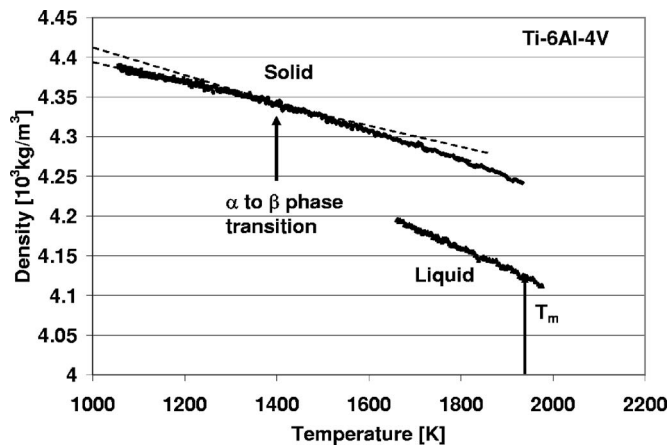


FIG. 2. Density of Ti64 vs the temperature for both solid and liquid phases.

was estimated by a closer examination of the temperature and the specific volume.

In the 1661–1977 K range the specific volume $V(T)$ of molten Ti64 exhibits a linear nature. The least-squares fit to the data is given by

$$V_{\text{liq}}(T) = V_{m,\text{liq}}[1 + 6.05 \times 10^{-5}(T - T_m)] \quad (1)$$

$\times (\text{m}^3/\text{kg}) \quad \text{over } 1661 \text{ K} \leq T \leq 1977 \text{ K},$

where $V_{m,\text{liq}} = 2.43 \times 10^{-4} \text{ m}^3/\text{kg}$ is the specific volume at T_m . Near the melting temperature the thermal expansion coefficient α_{liq} (K^{-1}) is given by 6.05×10^{-5} . The accuracy of the volume measurements was estimated to be $\pm 0.5\%$.⁷ Taking into consideration the 0.5% mass loss during the measurement, we estimate the total accuracy of specific volume and density to be $\sim 1\%$, which excludes the uncertainty in temperature.

The specific volume of β phase solid can be expressed by

$$V_{s,\beta}(T) = V_{m,\beta}[1 + 4.03 \times 10^{-5}(T - T_m)] \quad (2)$$

$\times (\text{m}^3/\text{kg}) \quad \text{over } 1661 \text{ K} \leq T \leq 1943 \text{ K},$

where $V_{m,\beta} = 2.36 \times 10^{-4} \text{ m}^3/\text{kg}$ is the specific volume of the β phase solid at T_m and 4.03×10^{-5} represents the volume expansion coefficient α_β (K^{-1}) near T_m . Shown in Fig. 2 is the sample density which is the inverse of the measured specific volume. The liquid density can be fitted by

$$\rho_{\text{liq}}(T) = 4122 - 0.254(T - T_m) (\text{kg m}^{-3}) \quad (3)$$

$\text{over } 1661 \text{ K} \leq T \leq 1977 \text{ K}.$

Comparing with pure titanium (Table I), the Ti64 melts at the same temperature as titanium at 1943 K. At the melt-

TABLE I. Properties of Ti64 in comparison with pure titanium at $T_m = 1943 \text{ K}$.

	Material			
	Liquid titanium	Liquid Ti6Al4V	Solid titanium	Solid Ti6Al4V
ρ (kg m^{-3})	4208	4122	4321	4246
α (K^{-1})	1.17×10^{-4}	6.05×10^{-5}	4.76×10^{-5}	4.03×10^{-5}
V (m^3/kg)	2.38×10^{-4}	2.43×10^{-4}	2.31×10^{-4}	2.36×10^{-4}
Reference	1	Present study	1	Present study

ing temperature, we have found that the liquid density of Ti64 is $\sim 5\%$ smaller than that of titanium; the solid density is 2% smaller than that of titanium; the liquid to solid volume change at melting temperature $(V_{\text{liq}} - V_{\text{cry}})/V_{\text{cry}}$ is 3.0% for both Ti64 and titanium. The thermal expansion coefficient of liquid Ti64 is $\sim 50\%$ smaller than that of liquid titanium while the thermal expansion coefficient of solid Ti64 is 15% smaller than that of solid titanium. This indicates that Ti64 should be favored in injection molding processes to avoid the shrinkage which causes cavities.

The thermal expansion coefficient difference between liquid and solid $\Delta\alpha_{\text{liq-cry}}$ ($\Delta\alpha_{\text{liq}} - \Delta\alpha_{\text{cry}}$) for Ti64 is $2.02 \times 10^{-5} \text{ K}^{-1}$ which is only $\sim 30\%$ that of titanium ($6.94 \times 10^{-5} \text{ K}^{-1}$). Such a difference in $\Delta\alpha_{\text{liq-cry}}$ between Ti64 and titanium reflects the difference in their kinetic properties in liquid state.⁹ The viscosity of a liquid, according to the Cohen-Grest free volume model,¹⁰ is

$$\eta = \eta_0 \exp(b\nu_m/\nu_f), \quad (4)$$

where ν_f denotes the average free volume per atom and $b\nu_m$ the critical volume for flow. The free volume of undercooled liquid can be expressed as $\nu_f = \nu_{fm}(1 - \Delta\alpha_{\text{liq-cry}}(T_m - T))$, where ν_{fm} is the free volume at melting temperature. Equation (4) shows that when a liquid is cooled below its melting temperature, its viscosity increases. Since $\Delta\alpha_{\text{liq-cry}}$ for Ti64 is smaller compared with that for titanium it is likely that the viscosity of Ti64 would increase more slowly than that of titanium at the same undercooling. Such speculation has yet to be validated in the upcoming experiments for viscosity.

In summary, a containerless approach of Ti64 volume measurement was carried out using the ESL at Caltech. The liquid temperature was varied over the temperature range of 1661–1977 K including 282 K of undercooling. Taking advantage of the capability that is specific to ESL we have measured specific volume, density, and thermal expansion coefficient of liquid Ti64. Liquid Ti64 is similar to liquid titanium in its density and volume change difference between liquid and solid at melting temperature, but its thermal expansion coefficient is only half of that of titanium.

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¹Paul-Francois Paradis and Won-Kyu Rhim, J. Chem. Thermodyn. **32**, 123 (2000).

²A. Cezairliyan, J. L. McClure, and R. Taylor, J. Res. Natl. Bur. Stand., Sect. A **81A**, 251 (1977).

³E. Kaschnitz, P. Reiter, and J. L. McClure, Int. J. Thermophys. **23**, 267 (2002).

⁴R. F. Brooks, J. A. J. Robinson, L. A. Chapman, and M. J. Richardson, High Temp. - High Press. **35/36**, 193 (2003/2004).

⁵H.-J. Fecht, *Microgravity Applications Program: Successful Teaming of Science and Industry*, edited by Andrew Wilson (European Space Agency, Noordwijk, The Netherlands, 2005), p. 8.

⁶W. K. Rhim, S. K. Chung, D. Barber, K. F. Man, G. Gutt, A. Rulison, and R. E. Spjut, Rev. Sci. Instrum. **64**, 2961 (1993).

⁷S. K. Chung, D. B. Thiessen, and W. K. Rhim, Rev. Sci. Instrum. **67**, 3175 (1996).

⁸J. Schroers, S. Bossuyt, W. K. Rhim, J. J. Z. Li, Z. H. Zhou, and W. L. Johnson, Rev. Sci. Instrum. **75**, 4523 (2004).

⁹B. Damaschke and K. Samwer, Appl. Phys. Lett. **75**, 2220 (1999).

¹⁰M. H. Cohen and G. S. Crest, Phys. Rev. B **20**, 1077 (1979).